A WIRELESS UNDERWATER TORQUE MEASUREMENT SYSTEM FOR SELF-PITCHING PROPELLERS

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1 Abstract

The even more large diffusion of self-pitching propellers leads to a more accurate analysis of their behaviour in running conditions, to avoid the onset of system instabilities under small deviations around the equilibrium working points. Unfortunately, the real time measurement of physical quantities in propellers' tests is a great challenge because of several intrinsic setups' complications due to submersed and rotating parts, restricted space for sensors and acquisition systems as well as data storage and transmission. In this paper the experimental setup developed to accomplish the WP's for the 7th FP project HYMAR is described. This setup is addressed to measure the torque acting on the blade as a function of pitch angle in particular around the equilibrium points at different speeds. The solution adopted is based on a wireless custom acquisition board placed inside the rotating shaft. The torque is measured using a miniaturized set of strain gages mounted on customized blades' joints. Data storage and transmission tasks have been achieved using an integrated on board memory and a 2.4 GHz transmitter module. This solution, that could appear a little bit strange for an underwater system, has the great advantage that it is possible to send and receive data using a probe containing a common USB Bluetooth adapter. Communication throughout water has been theoretically estimated and experimentally proved to be possible in water only for small distances (10-15 cm), but enough for this setup.

2 Introduction

This application has been implemented for the HYMAR FP 7th EU's project, studying the enhancement of a commercial torque-adapted self-pitching propeller. These kinds of propellers have the special feature to keep the best pitch angle according to the torque applied, so this lead to an enhanced efficiency throughout engines' speed range.
An accurate investigation of torque curve for fixed angles and speeds provides some fundamental parameters needed to characterize the propeller ad its behaviour in its operative range. The main task of this application is to obtain experimental torque curves to be compared with CFD numerical results in order to tune the numerical algorithm ad-hoc developed.
Unfortunately in this kind of experiments it is needed to acquire data in an unfriendly environment, with several constraint dictated by small dimension, rotating parts, physically unreachable measuring points and critical distances between different stages of the acquisition chain (i.e. sensors, signal conditioning, data analysis and transmission)
Moreover, the presence of the connection wires requires slip rings which add mechanical complexity and in general an accuracy reduction of the measurements.
Several commercial products partially comply with our experimental requirements[1], but the small room inside the propeller's shaft (ø 24mm) and the impossibility to change factory settings have led us to develop a full custom device, that is compliant with all our requirements and offers the flexibility to be employed in further applications, in a complete different setup, just performing small electronic and firmware adjustments.

[1] Microstrain SG-Link® -OEM-S: dimensions 58 mm x 50 mm x 26 mm (enclosure without antenna) 46 mm x 36 mm x 16 mm (circuit board assembly only). [9]

2.1 System overview

The technical solutions used in this setup for the realization of the wireless acquisition board and in particular for the battery power supply, signal conditioning, filtering, A/D conversion, data storage and transmission are based on a previous setup developed also by INSEAN, the WIMU [1]

In this case the amplification stage and filtering is completely new according with the experimental requirements and some adjustments have been done to allow the radio transmission through water. Indeed, the radio transmission through water has hard limitations due to absorption spectrum of this medium.

Moreover, in order to obtain quantitative information, the positioning of some sensors inside the propeller is needed. The acquisition system has to be not invasive and must preserve the working environment. In the meanwhile it would be more desirable to collect data without handling or disassembling the test equipment. Using the know-how acquired for WIMU [17], a wireless custom underwater torque and speed measurement system (WUTS) has been developed that complies with all the experimental requirements and overcomes the previous limitations, providing a real time monitoring and data acquisition device.

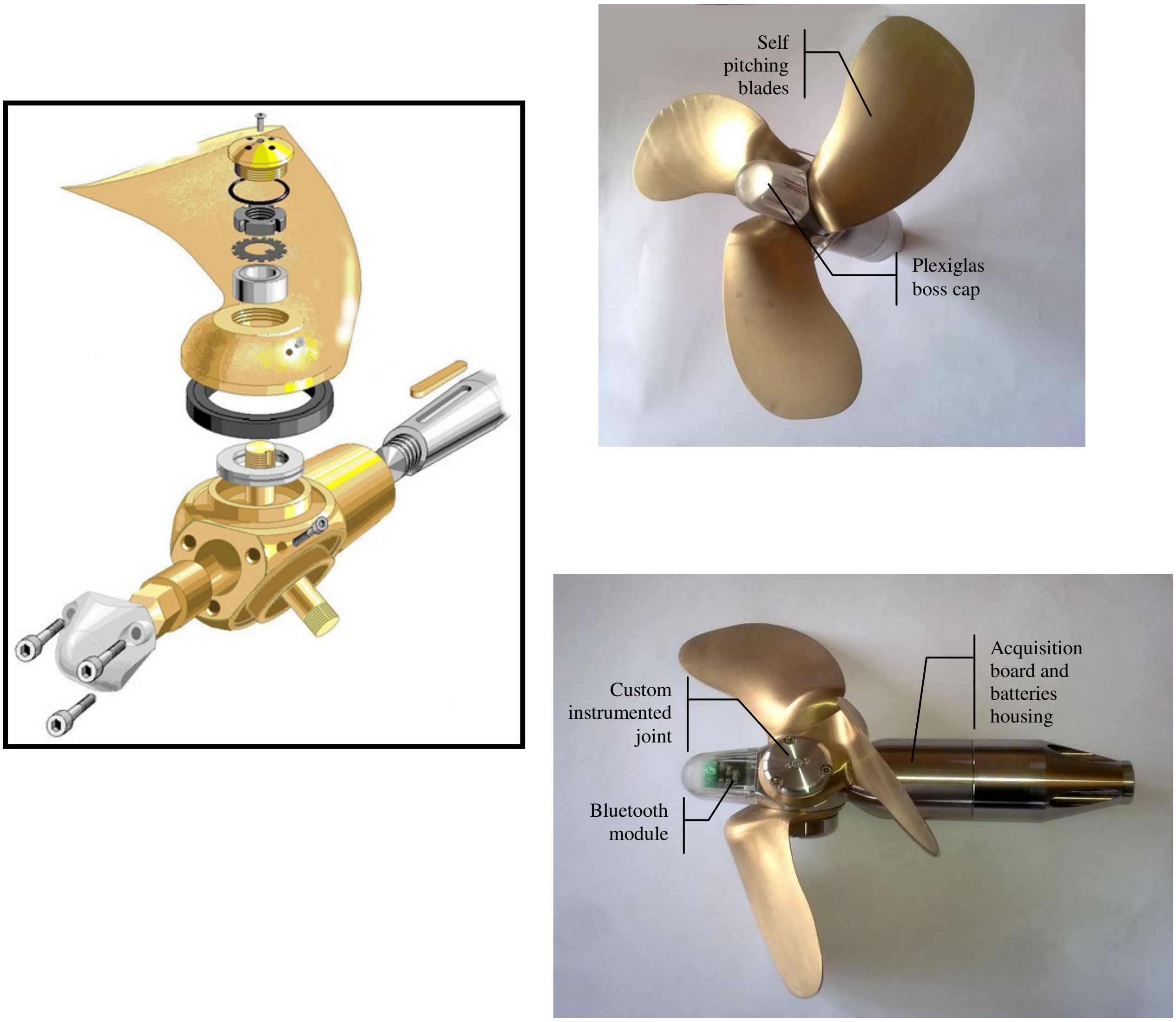

Figure 1 – Self pitching propeller's exploded view and mechanical main parts description

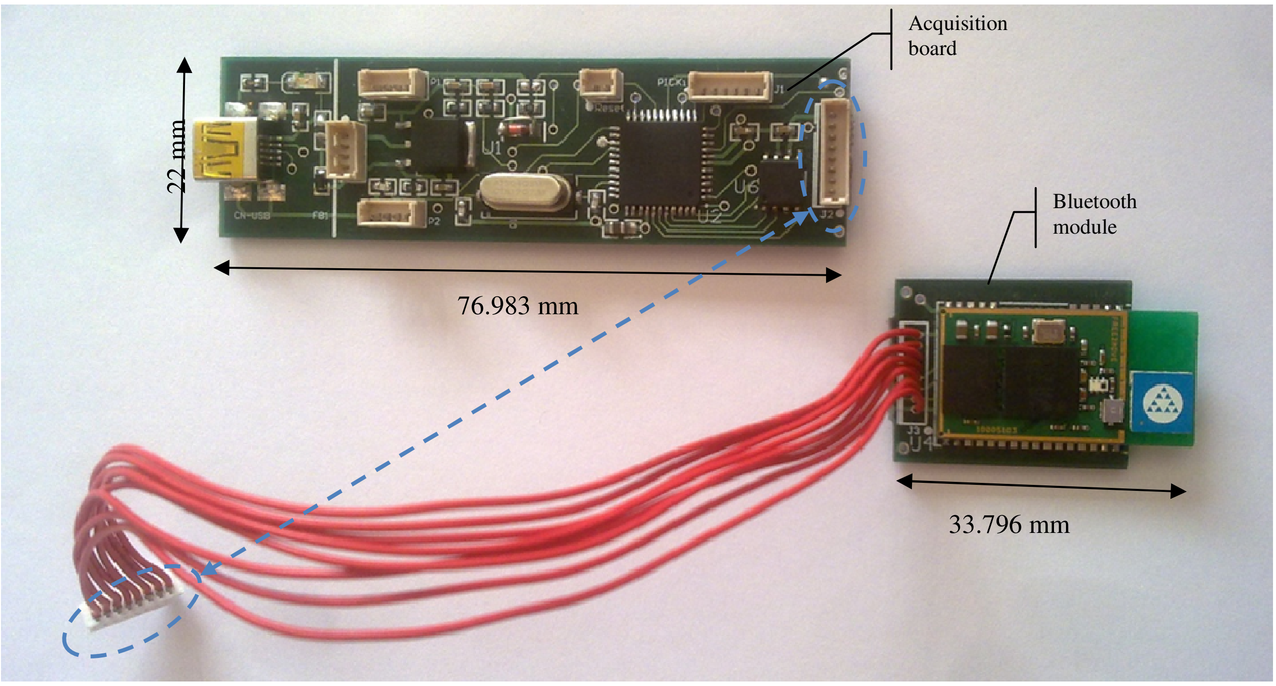

Figure 2 - the electronic board of WUTS

Referring to Figure 1 and Figure 2, all the acquisition chain is integrated on the same board, located inside the propeller's shaft, within its own power supply. The board is composed by two separable parts: one containing all the signal conditioning stage, acquisition core and data handling, the second is only equipped with the Bluetooth module and housed inside the Plexiglas made propeller's boss cap. A rear view of acquisition board, mounted inside the shaft with the batteries for power supply is shown in Figure 3

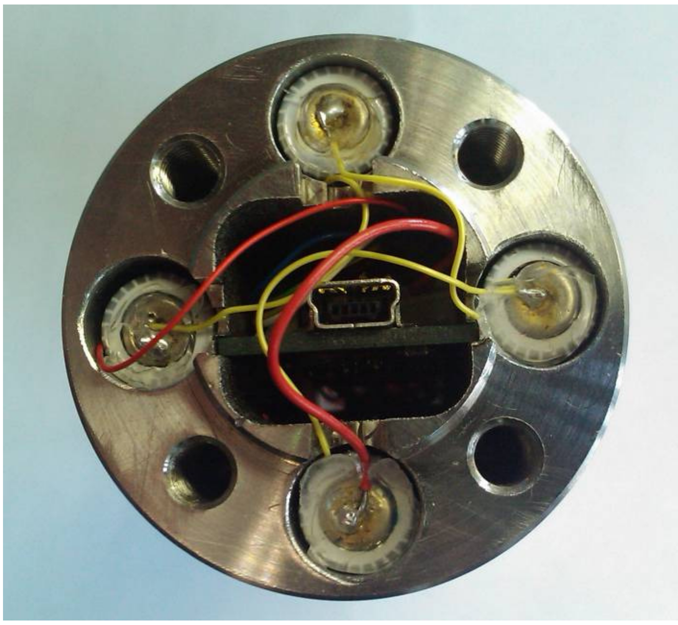

Figure 3 – Rear view: board and battery housing

This setup is a standalone system which is able to perform measurements, to manipulate physical quantities, to store collected data on board and to connect via wireless to an external laptop. The board is equipped with a Bluetooth module and data can be acquired in real time or stored on an on-

board memory and downloaded subsequently. In this way a common laptop can be used to acquire data without the needs to install any additional device.
The Bluetooth choice has been theoretically studied and empirically proved to be suitable for underwater transmission and our setup's distances, as discussed in wireless transmission paragraph.

3 Setup description

The propeller was mounted on the dynamometer shaft of the cavitation tunnel and it was visible and accessible through the transparent windows of tunnel's test section.
Investigations on propellers' behaviour, related to adjustable mechanical properties, imply to carry out information, not only from external measures, but also from data collected by sensors directly connected to moving parts involved in the experiment.
Being a rotating system, the entire acquisition apparatus needs to be placed inside the propeller, in a sealed housing. So, the first constraint was the dimension of the system: the electronic board, the battery pack and the Bluetooth antenna have been designed, chosen and arranged to fit inside the hub.
The Bluetooth wireless link was compliant with the requirement of making data accessible without modifying the equipment's setup for different test sessions. Moreover Bluetooth doesn't need a straight alignment as instead it is needed for IR transmission.
The measurement of torque on the blades' long axe is performed using strain gauges mounted on a custom support, in correspondence to the linkage between the blade and the hub. The rotating speed is calculated by the shaft encoder connected to a standard wired system but it is also acquired as well as using a tri-axial accelerometer installed on the electronic board.

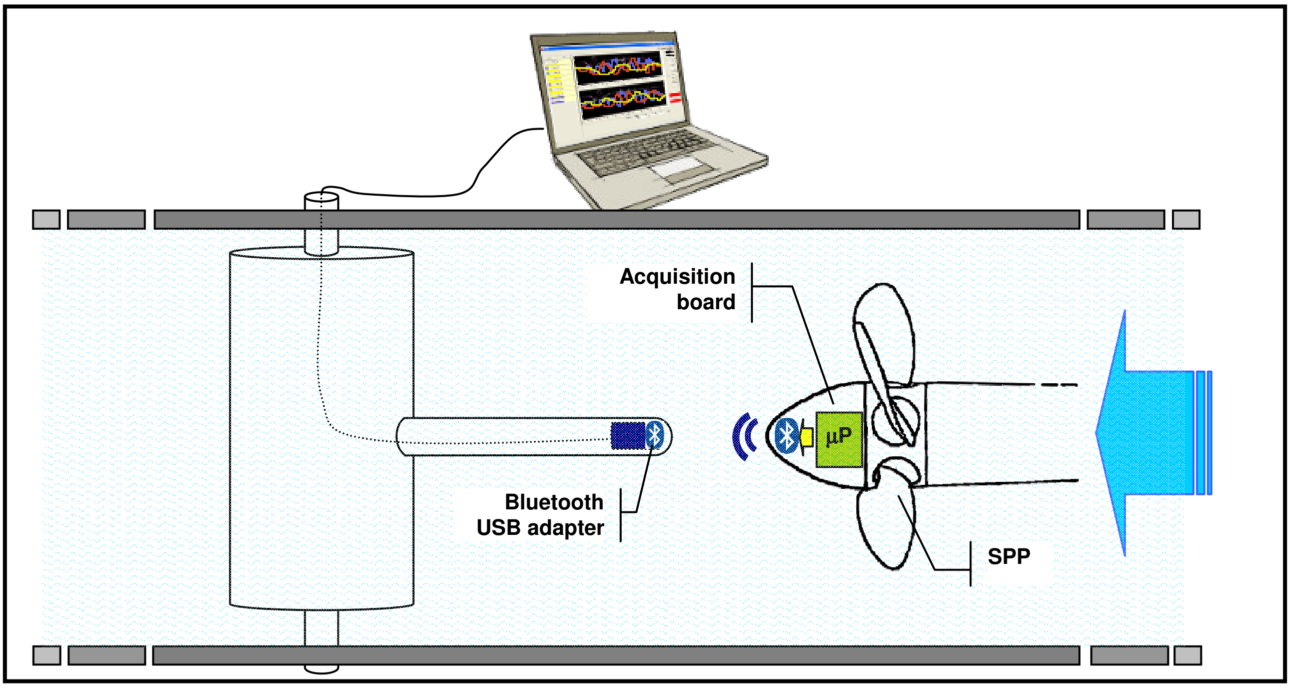

Figure 4 – Hymar experimental setup scheme

4 Technology development

The WUTS is a 'plug and play' system with the following features:
- Wireless transceiver technology.
- Embedded microcontroller.
- Mems technology for accelerometers.
- Embedded signal conditioning.

All these components are integrated on the same board so to obtain a robust a compact design. The electronic components are housed inside the propeller's shaft within power supply batteries.

4.1 Wireless Underwater Torque Measurement System (WUTS)

The system architecture is mainly composed by strain gages and mems accelerometer as sensors, a signal conditioning amplifier, an analog to digital converter, a processing/control hardware and by wireless 2.4 GHz module.. The high-level electronic architecture is shown in Figure 5 - WUTS Architecture.

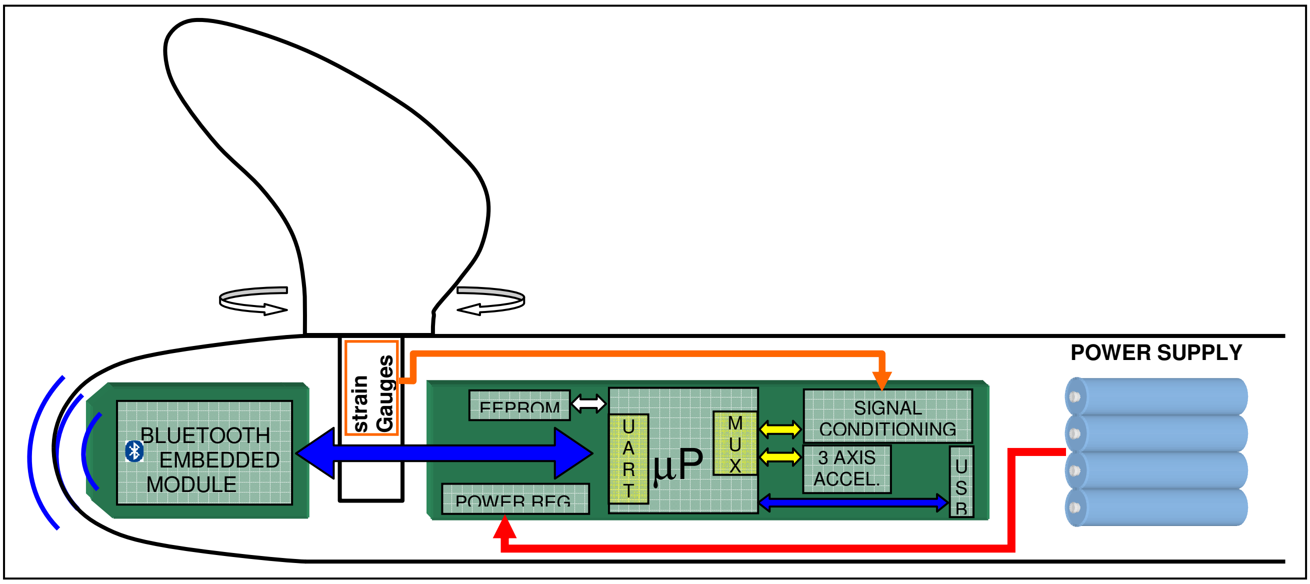

Figure 5 - WUTS Architecture

4.2 Components description

The design specifications can be shown starting from the block diagram of Figure 6.

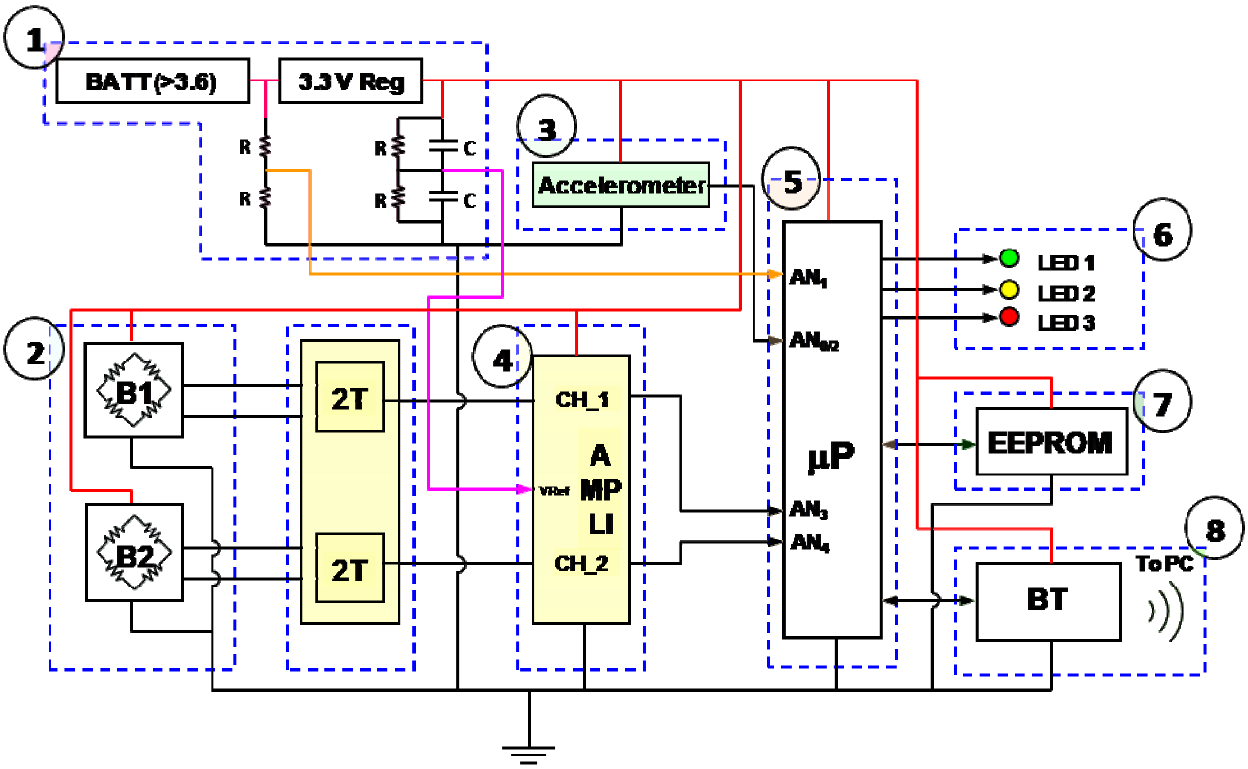

Figure 6 – Block diagram

Referring to picture numbering, the system is composed by the following parts:

1. Power and reference voltage.
2. Strain gauges.
3. Tri-axial accelerometer.
4. Amplification stage.
5. The microprocessor (µP).
6. 3 leds interface.
7. The on board memory.
8. The wireless module.

4.2.1 *Power and reference voltage*

Because of the underwater set-up, the transduction system and the electronic device for the acquisition must be sealed and insulated, so all equipments must be powered by batteries housed within the electronics in the rotating part of the shaft. A low power electronic design it is needed to reduce weight and space required by batteries and to simplify the mechanical design.
All the board works using a voltage of 3.3 volts regulated by an LDO (Low Dropout regulator). The power input to the LDO comes from 4 rechargeable Nimh 1.2V cells.
The powered devices are:

- The microprocessor.
- The amplifier.
- The accelerometer.
- The radio communication Bluetooth (BT) module.
- The EEPROM.

Using a single supply it is needed to provide a common reference level for amplifiers, as close as possible to the midpoint of the excursion of the ADC (1.65 V). The reference source is a couple of capacitor and resistance, as shown in Figure 7 so that the voltage reference (Vref) is equal to Vcc/2. This power supply scheme has been chosen to allow to the torque measurement to be independent from the Vcc value. This feature will be described more in details in the next paragraph, together with the amplification scheme.

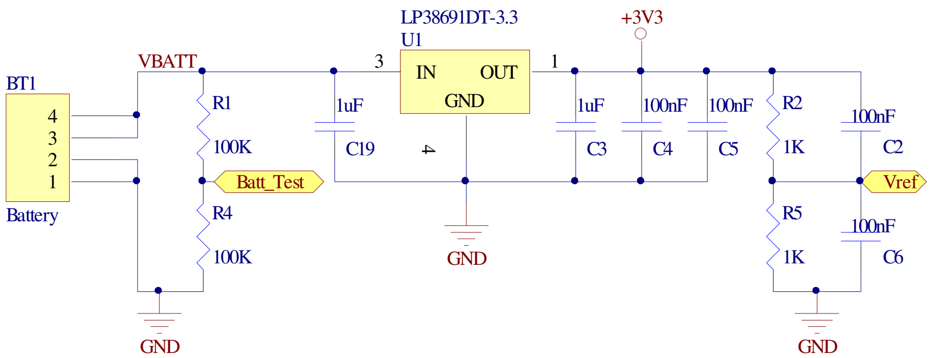

Figure 7 – Power regulation and reference voltage stage

4.2.2 *Amplification stage*

The signal of the bridge ranges approximately from -0.001V to +0.001V, so a signal conditioning with a gain of about 540, operating with a 3.3v single supply has been designed using an high-gain differential amplifier before the A/D converter. The scheme of the amplifier and signal conditioning is shown in Figure 8.

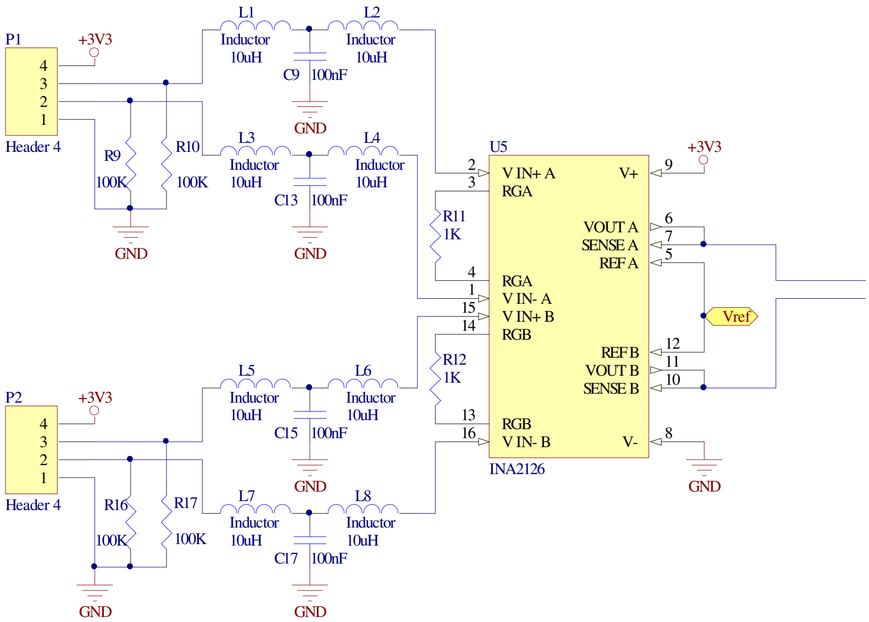

Figure 8 - Amplification, bridges regulation and filtering stage

The MicroPower instrumentation amplifier INA2126 [3] , has been chosen because of the following features that well fit in a low voltage battery operated application :

- Wide supply range: ±1.35V to ±18V
- Rail-to-rail input 0-3.3 volts.
- Variable amplification by changing only a resistor R_g (R11 and R12 in Figure 8) obtaining amplification factor $A=5+(80k/R_g)$, up to 10000V/V.
- Low quiescent current (175µA/channel).

Before the amplifier a T filter, with a low pass cut off frequency close to 100 khz has been inserted to reduce the high frequency noise at the input of the amplifier. This filtering stage helps also to reduce the effects on the output of the high frequency common mode noise that cannot be rejected by the amplifier as shown in Figure 9.

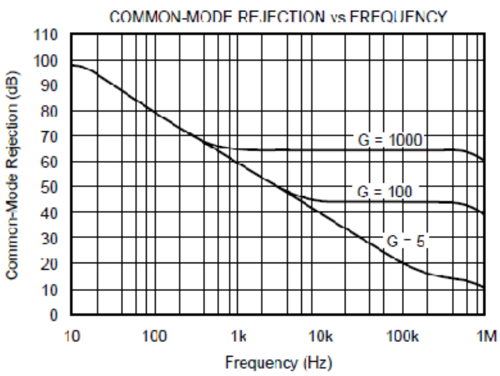

Figure 9 Common mode rejection of INA 2126

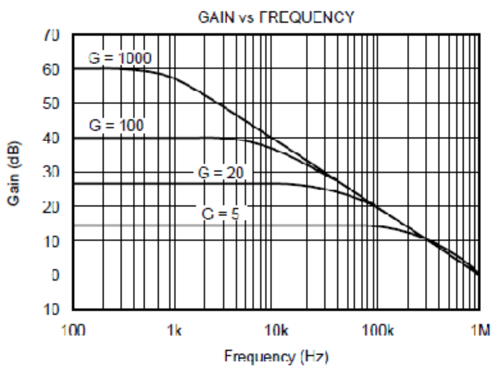

Figure 10 INA2126: Bandwidth

The selected gain (Ga) for this application is approximately 500, and so the transfer function of the amplifier (figure 10) can be approximated to a constant gain of 500 and a single pole low pass filter with a cut off frequency of 1.5 Khz.
In the frequency range 0- 1Khz the voltage output Vu can be written as:

$$V_u = V_{ref} + V_{cc} \bullet G_a \bullet K_s \bullet U \qquad \textbf{Eq. (1)}$$

where V_{ref} is the voltage reference(see Figure 7, Figure 8), V_{cc} is the voltage supply,3.3V, K_s is the gauge factor, Ga is the amplifier gain, and U is the measured strain. Then considering that $V_{ref}=V_{cc/2}$, the equation 1 becomes:

$$V_u = V_{cc}\left(\frac{1}{2} + K_s \bullet G_a \bullet U\right) \qquad \textbf{Eq. (2)}$$

4.2.3 *The microprocessor (μP)*

The core of WUTS is a Microchip Pic 18f4553 [6] . This device has several useful features for our application:

- External interrupts used for time base synchronization.
- 3 16 bit timer modules used for clock generation.
- Enhancetd USART module used for Bluetooth interface.
- 12-bit, A/D Converter module with programmable acquisition time up to 100KHz.
- SPI module used for data transaction to/from EEPROM.
- USB V2.0.
- Wide operating voltage range (2.0V to 5.5V).

Another feature of this microcontroller is the possibility to control the CPU clock, from 32 KHZ to 48 MHz in order to reduce the power consumption when the data acquisition process is stopped increasing battery duration.

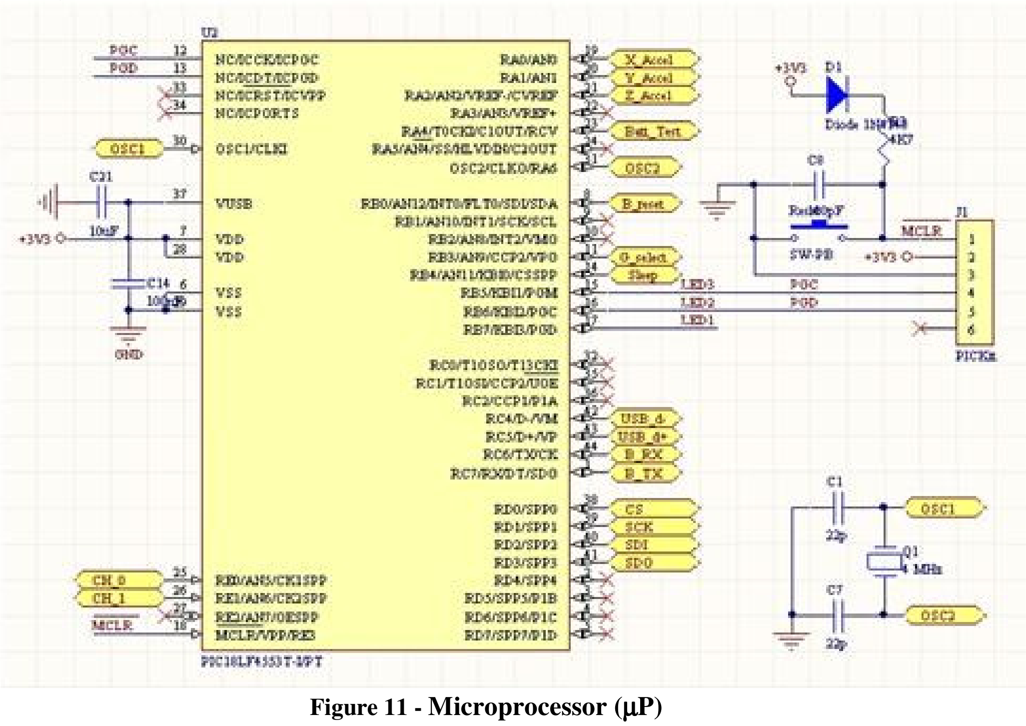

Figure 11 - Microprocessor (μP)

The acquisition stage is based on the 12 bit A/D converter which can be multiplexed to 13 input pins. In this application 6 channels are used: 3 accelerometers, 2 strain gauges and 1 channel to check battery status. The A/D converter module uses as reference voltage the supply of

Microcontroller, 3.3V (V_{cc}) . Accelerometers and amplified signal of strain gauges can be directly connected to microcontroller pins because their output signals range from GND to power supply voltage V_{cc}.
It is interesting to observe that the acquisition chain is ratiometric. The two great advantages of this configuration are:

1. The converted digital output does not depend by the voltage supply level.
2. The zero level of the output swing follows Vcc/2.

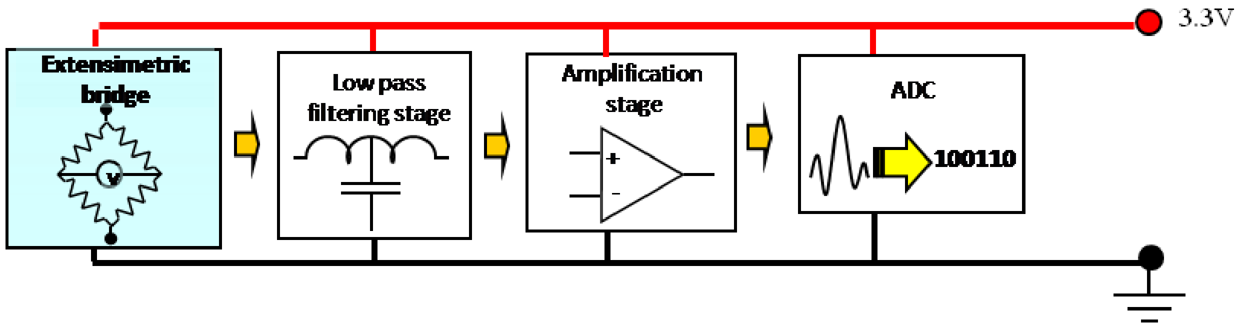

Figure 12 - Power supply distribution in a ratiometric acquisition chain

To better understand this condition it is needed to calculate the conversion output.
The conversion output D_o of the 12 bit A/D converter, for a given input V_i, can be expressed by:

$$D_o = \frac{V_i}{V_{cc}} \bullet 4096 \qquad \text{Eq. (3)}$$

Considering also that V_i in Eq. (3) can be substituted by V_u of

$$V_u = V_{cc}\left(\frac{1}{2} + K_s \bullet G_a \bullet U\right) \qquad \text{Eq. (2)}$$

we have:

$$D_o = \frac{V_{cc}\left(\frac{1}{2} + K_s \bullet G_a \bullet U\right)}{V_{cc}} \bullet 4096 = \frac{(1 + 2 \bullet K_s \bullet G_a \bullet U)}{2} \bullet 4096 \qquad \text{Eq. (4)}$$

Then the output of the A/D converter is independent from the supply voltage and this feature allows us to use a battery power supply with a simple linear regulator.
Figure 13 shows the measured output by the A/D under a certain constant load of the bridge when the power supply changes from 3.0 V to 3.6V.

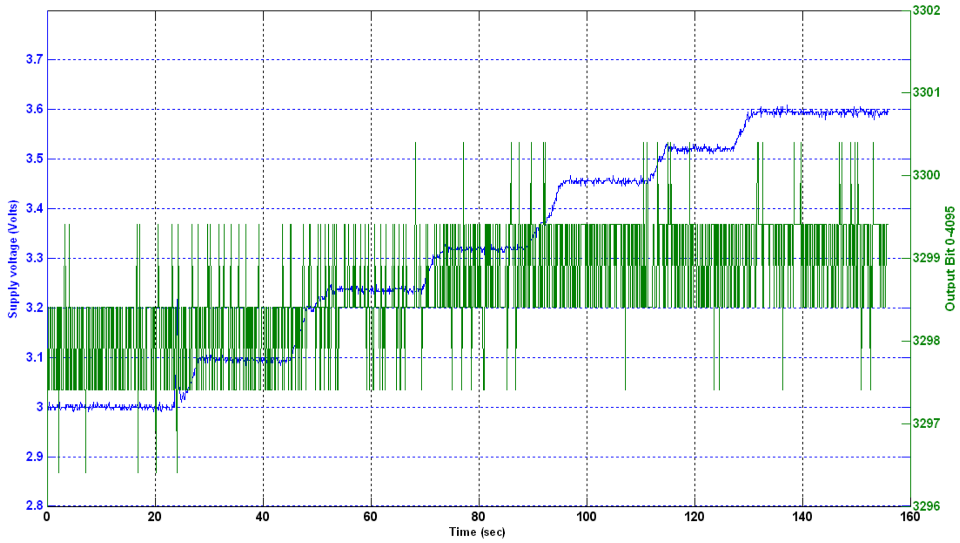

Figure 13

In practice the sensitivity of the output to the power supply variation cannot be measured in this range (+0.3V, -0.3V) of voltage supply variation. The chosen linear voltage regulator, National LP38691 has a voltage output precision over the full temperature range of 2%. (+/- 0.07 V at 3.3V).

4.2.4 *Anti aliasing Filtering*

The microprocessor could sample the data up to 100 Khz but, in this application a sampling frequency of 100 Hz is enough. The high acquisition rate it is also used as oversampling, to avoid the need of using a dedicated low pass filter. Independently by the selected sampling time for the output data, the microprocessor always samples at its maximum frequency, (50 Khz using two channels). The requested sampling rate is obtained averaging the samples acquired in a time interval. As example at 100Hz, enabling two channels each sample is calculated as average on 500 samples. In this setup only two channels are enabled, the bridge channel and one of the accelerometers and the effective sampling frequency is 50Khz. Moreover the bridge has the amplifier with a low pass transfer function with a cut off frequency close to 1 khz, and the accelerometer a single pole low filter at the same frequency.

4.2.5 *Strain gauges*

The torque measurement is done using strain gauges in full bridge configuration.

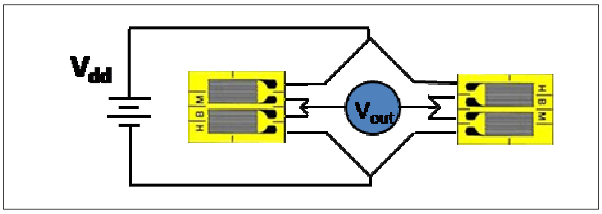

Figure 14 – Full bridge configuration diagram

A couple of Y series HBM shear/torsion half bridge strain gages [2] were mounted on the opposite surfaces of the custom blade’s joint by the propeller’s hub, to create a full bridge configuration as shown in Figure 15. This configuration has temperature compensation as well as great sensitivity enhancement.

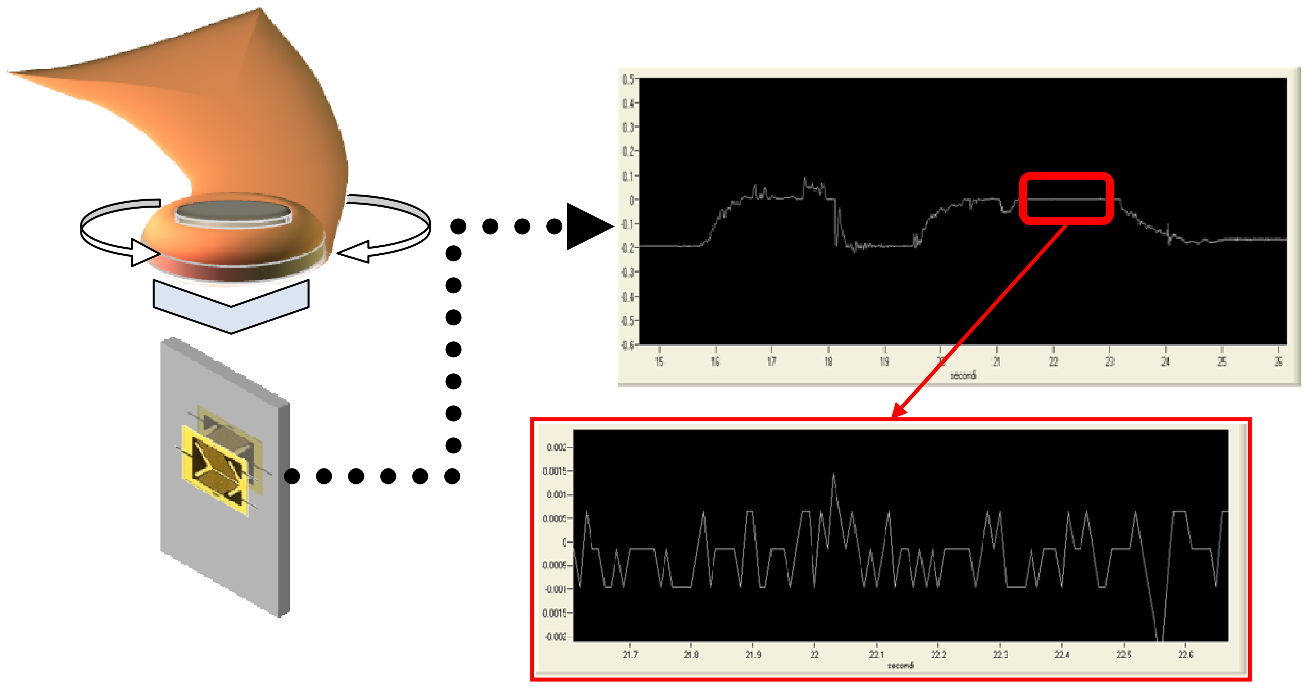

Figure 15 – Strain gauges positioning and acquired data

A torque calibration setup, shown in Figure 16, has been used to evaluate linearity errors and noise. The maximum linearity error on the torque measured by strain gages' is about 0.6% (Figure 17) and the noise affects only the less significant bit as shown in Figure 15.

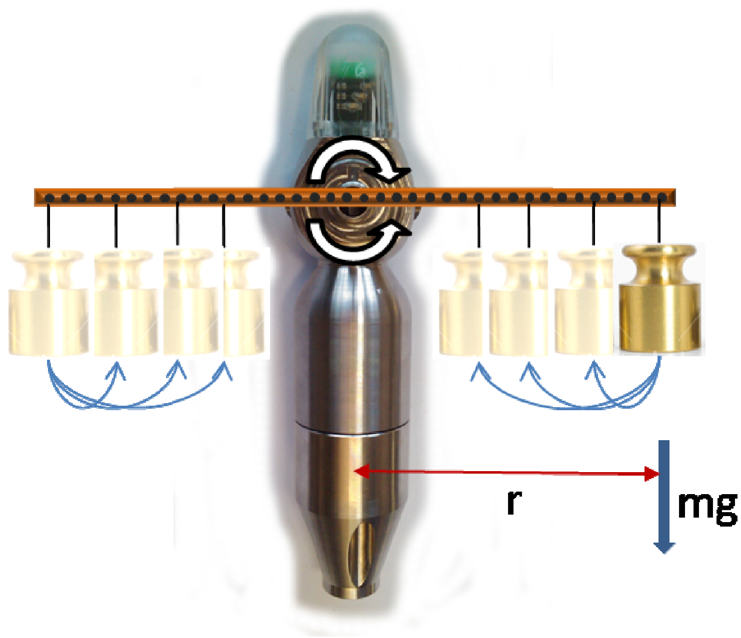

Figure 16 – Torque measurement calibration scheme

Channel output (Volts)	Theoretical momentum (N*m)	Linearized measure (N*m)	Measure error (%)
-1.15464	0.829301	0.833996472	0.40%
-0.98466	0.710829	0.711219918	0.03%
-0.81678	0.592358	0.589960194	-0.20%
-0.65736	0.473886	0.474811128	0.08%
-0.49314	0.355415	0.356195022	0.07%
-0.3378	0.236943	0.24399294	0.59%
0.00018	0.000000	-0.000130014	-0.01%

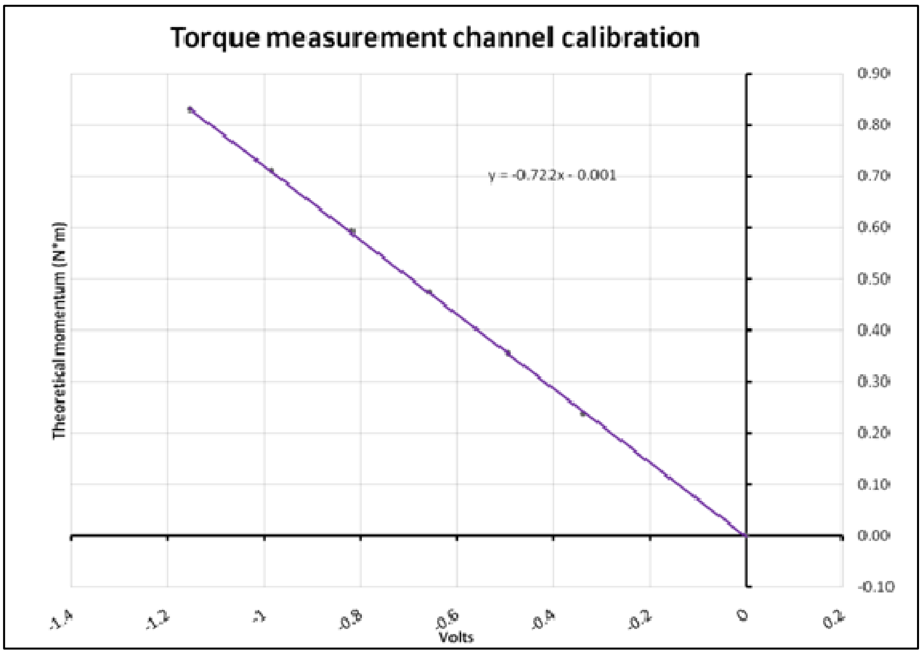

Figure 17 – Torque measurement channel calibration

The range of measured torque, with the selected gain is +/- 0.8Nm. Reducing the gain the range could be extended up to +/- 3Nm, a value that can be considered the mechanical limit of the system.

4.2.6 *Tri-axial accelerometer*

A tri-axial accelerometer has been used to calculate the value of revolutions per second of the shaft. The MEMS accelerometer is the MMA7331 [7] provided by FREESCALE, with these features:

- Temperature compensation.
- Gain selection among 2 sensitivities
- Zero-g offset factory set.

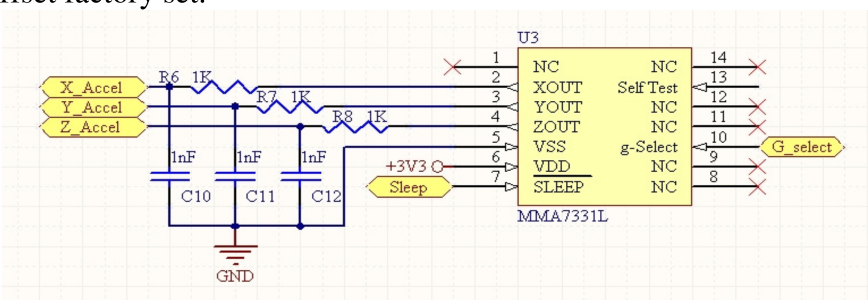

Figure 18 - Tri-axial accelerometer

4.2.7 *The on board memory*

During an acquisition the whole process of acquisition of data collected by the strain gauges is stored locally in a non volatile EEPROM with 64 Mbytes of capacity [5] .
At the end of acquisition (in "offline" mode) data read by the microprocessor from the EEPROM, are transmitted through a specific protocol via BT antenna connected to the PC acquisition.

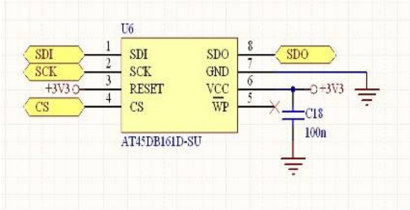

Figure 19 - EEPROM ATMEL

4.2.8 *The wireless module*

For this kind of setup, an easy way to communicate data to a recording system on the PC is through a radio link using Bluetooth as communication protocol. A BT wireless communication channel has been realized inserting a high power FREE2MOVE Bluetooth module [4] into the propeller's bulb and coupled to a USB Bluetooth adapter, placed in a sealed housing, on the face of it, connected to the laptop.
In case of unexpected or massive interference to the outgoing flow from the propeller, is possible also to use during the acquisition, the local memory to store the collected data

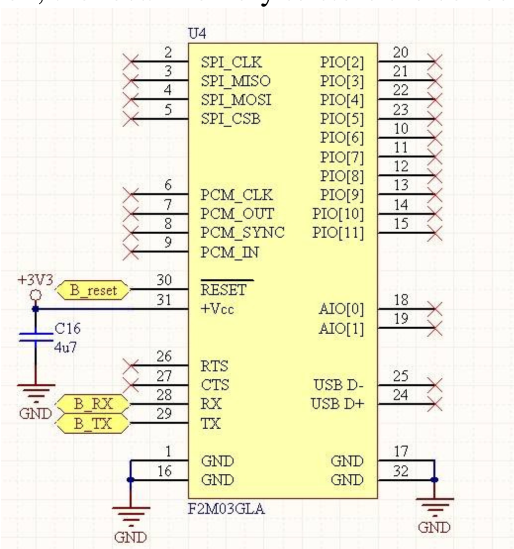

Figure 20 - The Bluetooth embedded module

5 INTEGRATION OF WUTS

The mechanical dimensions of the board were the main constraint of the project because it had to fit inside the hollow propeller's shaft. So the electronic integration had to fulfil experimental requirements as well as to be flexible and customizable.
Moreover, considering that in this application the board rotates together with the shaft, all the components must be as much as possible light and close to the rotational axis to reduce vibrations and forces acting on the single parts.

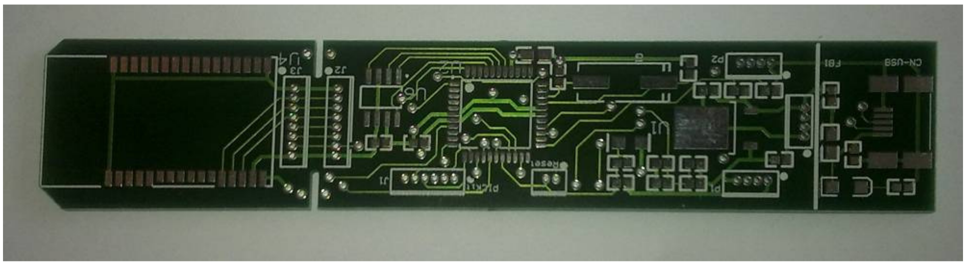

Figure 21 - PCB realization

The placement of all the electronics components has been done taking in account the system balancing an in particular the accelerometer is positioned with one of its 3 sensitive axes on the rotational axis of the shaft. In this way, the offset due to the centripetal acceleration is theoretically zero.
The board is designed to be eventually spit up along its longitudinal direction, close to the Wireless module, so it is possible to have a smaller board containing only the radio communication and a stage for acquisition core. In the case of splitting, two plugs replicate all the connections provided for the two parts (Figure 1 – Self pitching propeller's exploded view and mechanical main parts descriptionand Figure 21).
Fine adjustment of the bridges' offset is possible by inserting and/or changing two additional resistors provided for both channels.

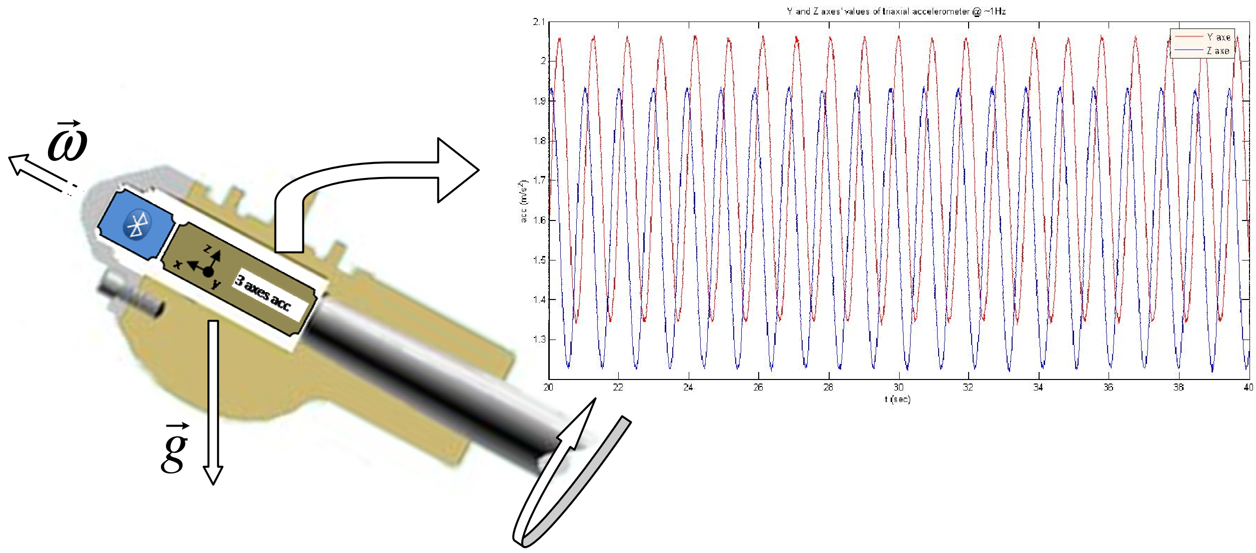

Figure 22 - Three axes accelerometer output for system rotating at ~ 1Hz

The accelerometers mounted with the X axis in the direction of the main length measures the angular speed of the shaft using is the gravity component of acceleration that, due to the rotation, has the following expression:

$$a_{gy}(t) = g \cdot \sin\alpha \cdot \omega t \qquad \text{Eq. (5)}$$

where α is the inclination angle of the shaft (α=0 for a horizontal shaft).
A three axes accelerometer has been chosen in order to have redundant information improving data reliability. Using this configuration the gravity signal has the same frequency of shaft's rotation whit amplitude of $g \cdot \sin\alpha$.
This sensors integration makes the acquisition system fully autonomous, measuring all the physical quantities needed to have a complete set of information for this kind of experiment.
The motherboard also contains signal conditioning circuitry, the microprocessor and the Bluetooth module.
The firmware developed for this unit collects data from sensors, performs the angular speed calculation and allows storing all the parameters of each channel like sensitivity, name, max range, last zero in a non volatile eeprom and can be updated via Bluetooth.
Therefore it is possible to perform the tests using different computers without exchange the sensor parameters.

6 WIRELESS COMUNICATION

The WUTS uses a 2.4 GHz high power transmitter with the complete Bluetooth stack implemented on the module. This means that the wireless link appears o the microprocessor like a common serial interface at 115200 bd. A clear advantage in using the Bluetooth is the software compatibility with the applications based on a serial communication.
The power consumption of these devices and the typical voltage supply (3.3v) fits with the requirements of a battery operated application.
The WUTS use as Bluetooth transmitter the F2M03GLA [4] module produced by FREE2MOVE.

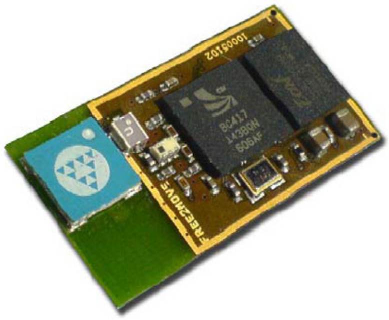

Figure 23 - Bluetooth module.

This module has an integrated antenna, serial interface, and a Range up to 350m in outdoor (line of sight).
The theoretical maximum data rate is 3 Mbit but in this application the chosen data rate 115 Kbit enough to guarantee the real time transmission of 10 channels with 16 bit of resolution 500 Hz.

6.1 Underwater transmission

Underwater wireless communication is a very hard challenge because of signal degradation due to refraction passing through different medium and transmission's attenuation in water. There are few applications in this field but mostly using high power radio transmitters [8].
To a first approximation we can leave out attenuation in air and refractions. Considering only the distance to be covered in water, the signal will be attenuated of a factor 1/e (63% attenuation) after a penetration distance D_p. D_p, at 2.45 GHz, is defined as follow:

$$D_p = 1.947 \cdot \frac{\sqrt{\varepsilon_r^{'}}}{Lf}$$
Eq. (6)

Where ε_r' is the dielectric constant and Lf is the loss factor, that give a measure of heat conversion efficiency.

Some tests were performed to evaluate the possibility of Bluetooth underwater transmission and extract a set of devices useful for our purpose. In our test, taking into account water temperature and conductivity, $\varepsilon_{r'}$=78 and Lf=14 so Dp=1.2 cm.

Transmitting device is a class 1 Bluetooth module with 6.3 dBm transmission power and receiving device has a sensitivity of -80dBm, so communication should be possible over a distance greater than 10 cm.

Some measurements have been performed reaching a maximum distance of about 15 cm in calm water with a baud rate of 115Kb. This result is enough for our application that needs of a shorter transmission distance although in flowing and perturbed water.

7 Conclusions and future works

This paper describes a highly integrated wireless torque measurement system that addresses the issues of flexibility, power-efficiency and size. Some solution about sensor integration in a submergible, battery operated system and wireless radio link reliability are implemented and tested. This device has been used to perform tests on a self pitching propeller measuring the torque as a function of the pitch angle over the full operative speed range.

The modular nature of the system and the plug and play capability allows to easily changing the sensor or replacing with another voltage output transducer so to realize different setup for other towing tank typical test.

Further developments could be an additional magnetic switch to disable power supply without disassembling the propeller, and a new mechanical design that allows measuring also the torque and trust applied on the shaft using the same board.

8 Acknowledgment

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